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SALT Orbit Determination Covariance Analysis Using GPS Tracking

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Introduction

In addition to hosting an altimeter for oceanographic measurements, the SALT satellite was also to carry on board a light weight, 2-channel GPS receiver designed by Rockwell International [*Weninger et al.*, 1989]. In this report we present results of a covariance analysis of the radial precision of non-real-time GPS-derived SALT orbits. For comparison, we have also computed solutions for a GPS receiver similar to the one which will be launched on Topex [*Galbraith*, 1990].

Covariance Analysis

Software and Mathematical Models

The covariance analysis was performed using the OASIS software package developed by the Jet Propulsion Laboratory. OASIS operates by reducing the orbit determination problem to a system of linear equations which it solves using a batch-sequential (Kalman) process noise filter; state parameter estimates and the associated covariance are computed at each epoch. As well as estimating constant state parameters, the OASIS filter permits stochastic estimation of parameters. It also provides for consider covariance analysis to evaluate the accuracy of parameter estimates under possible filter mismodeling scenarios. The mathematical models in OASIS are described by *Wu et al.* [1986].

We assumed that the GPS constellation consisted of 21 satellites in 6 orbital planes. The orbital planes were equally spaced about the Earth with an inclination of 55 degrees with respect to the equatorial plane. Initial conditions were provided for each satellite, and the equations of motion were then integrated to provide nominal trajectories for the satellites. All subsequent state partials and observation residuals were computed based on the values of the satellite states. For the GPS satellites, the dynamic force model included zonal gravity coefficients up to degree 8, while sectoral and tesseral harmonics were also selected up to degree and order 8.

SALT was modelled at an 800 km altitude and inclination of 108 degrees. The nominal data arc for SALT was 100 minutes. The covariance analysis used a 120 minute time period. The gravity field had selected terms up to degree 50 and order 41. Nominal values for these coefficients and their corresponding uncertainties were determined from the Goddard Earth Model T2 (GEM-T2) [*Marsh et al.*, 1990]. A Jacchia-Walker atmospheric model was used to study the effects of atmospheric drag on the spacecraft. The solar radiation pressure modelling is described by *Wu et al.* [1986].

Receiver Simulation

To properly simulate the performance of a GPS receiver on board a low Earth orbiter, one must know the noise properties of the data types produced by the receiver, how often measurements are made, and which GPS satellites are tracked. Most space qualified GPS receivers currently available have fewer tracking channels than the number of GPS satellites which are in view at any time. Thus, an algorithm is used to determine which satellites to track, in order to optimize the scientific mission of the satellite. The SPINSAT GPS receiver (hereafter termed the "Rockwell" receiver) is a sequencing receiver with 2 channels. It tracks one pair of satellites for one second, acquires a different pair for the next second, then reacquires the original pair and so on; the Rockwell selection algorithm chooses the two satellite pairs (i.e. 4 satellites) with the lowest Positional Dilution of Precision (PDOP) value. The available data types are p-code pseudorange and range rate. No carrier phase data are provided. The receiver can operate on either L_1 or L_2 frequencies. In practice, the receiver tracks on L_1, and makes occasional L_2 measurements to provide an ionospheric correction. Although the Rockwell receiver would have produced measurements every second, the OASIS software could not accommodate such a high data rate. Therefore, we assumed that observations from adjacent time points (i.e. those satellite pairs separated by 1 second) could be interpolated to a common epoch and then processed as simultaneous observations. Finally, we analyzed the satellite selection algorithm over a number of data rates and found that the satellite geometry did not appreciably change over 30 seconds, and adopted 30 seconds as our batch interval. In other words, we simulated the Rockwell observations as a simultaneous measurements from 4 satellites every 30 seconds.

The tracking algorithm for the Topex receiver manufactured by Motorola (hereafter termed the "Topex" receiver) was entirely different than the Rockwell receiver algorithm. The Topex receiver has 6 channels which will simultaneously track L_1 and L_2 frequencies. The data types are p-code pseudorange and carrier phase. The satellite selection algorithm is discussed by *Wu et al.* [1989]. Instead of relying entirely on minimizing PDOP, a carrier phase receiver must also take into account long-tracking scenarios. For optimal carrier phase tracking, a satellite must be viewed long enough to estimate the carrier phase ambiguity. As a rule of thumb, satellites must be tracked more than 30 minutes. *Wu et al.* [1989] also suggest that GPS satellites viewed by the low Earth orbiter be visible from one or more ground tracking stations. We used the algorithm of *Wu et al.*

[1989], and chose to maximize the viewing period (level 2 in their paper). Since the satellites were tracked over long periods of time, we were able to use a longer batch interval for the Topex receiver (5 minutes).

Figure 1 shows the selected GPS satellites which where tracked by SALT using the Rockwell and Topex algorithms. The Topex selections are tracked at least 30 minutes (excluding the beginning and ending of the data arc). The Rockwell selections show greater variability - with satellites being tracked anywhere from 60 seconds to 20 minutes. One second precision values for these two receivers are shown in Table 1. This information will be discussed more fully when data weights are chosen for the covariance analysis. While the Topex receiver pseudorange error should not exceed 60 cm for 1 second averaging times [*Galbraith*, 1990], the maximum Rockwell receiver pseudorange noise value at 1 second is 250 cm. Additionally, the Topex receiver has high precision carrier phase data available. If the carrier phase ambiguity can be resolved, this converts the carrier phase data into very high precision "carrier range" data.

Tracking Network

SALT orbital accuracy will also be dependent on the size and strength of the ground tracking network. We have chosen to study the tracking stations which are listed in Table 2. Since this covariance analysis was to address the orbit accuracy of a satellite to be launched in the summer of 1991, these stations were originally chosen to reflect actual continuously operating GPS receivers. We chose a base network of 6 stations. A similar network will be used by NASA to track Topex. Three of these stations are located at the Deep Space Network (DSN) installations in California, Australia, and Spain (Network A). The DSN sites have been measured with very long baseline interferometry over many years, and their positions are known to better than 5 cm. The remaining stations are located in Japan, Brazil, and South Africa (Network B), and were chosen to optimize global coverage. The additional ground stations, Kokee, Westford, Richmond, and Wetzell (Network C), are part of the Cooperative International GPS NETwork (CIGNET). Kokee adds strength over the Pacific Ocean. Westford, Richmond, and Wetzell have a long history of measurements with VLBI and SLR. They are regularly used to determine Earth orientation parameters.

The ground tracking stations were assumed to be equipped with GPS receivers similar to JPL's Rogue receiver (which can track up to 8 satellites), with both low-noise pseudorange and carrier phase data observables. This receiver can operate in either a code-correlating or codeless mode. Observations were generated for the ground tracking sites for all satellites which were greater than 10 degrees above the local horizon. This restriction is adopted to reduce site-dependent multipath noise and atmospheric refraction. The pseudorange and carrier phase data weights were selected based on previous studies [*Wu et al.*, 1989].

Estimation strategy

Our SALT orbit estimation strategy is based on analysis techniques presently being used in the GIPSY and OASIS softwares [*Lichten and Border*, 1987; *Larson*, 1990] for GPS orbit determination. Strategies from Topex studies have also been adopted [*Wu et al.*, 1989]. Summaries of our tracking simulations and filter inputs are shown in Tables 3 and 4. We discuss the assumptions in both tables in turn.

Since our SALT error analysis will depend on our assumptions of the measurement precision, we must address the validity of the data weights we adopted. We took the manufacturer's listed 1 second data noise shown in Table 1 and assumed that we could interpolate these values into "normal" points at our batch intervals. For the Rockwell receiver, this meant 15 data epochs were compressed into a 30 second batch, since each satellite was tracked *every other* second. Since the ionosphere is difficult to model, we assumed that a dual frequency ionosphere corrected data type was formed, which results in data noise larger by a factor of 3 [*Lichten and Border*, 1987]. We slightly penalized the Rockwell receiver (by 10%) because the L_2 corrections would not be simultaneous. The Topex data weights were determined in an analogous manner, although the batch interval was 300 seconds. The data weights we used for the ground tracking network were taken from *Wu et al.* [1989], although we chose a more conservative pseudorange data weight, 10 cm rather than 5 cm. Since multipath can contribute significant non-random error to pseudorange data, we felt that a conservative weighting scheme was justified.

The SALT orbit determination problem relies heavily on how effectively the GPS orbit errors can be reduced. The GPS orbits are determined by tracking the GPS satellites with globally distributed ground receivers. If the positions of the ground trackers are well known, the accuracy of the ground network (often called a "fiducial network") is transferred to the GPS satellites, resulting in sub-meter orbits [*Lichten et al.*, 1989]. We have chosen to fix the positions of the DSN sites (Australia, California, and Spain). Although we know the positions of the other tracking sites to better than 10 cm, from previous VLBI and SLR, we have not constrained the station positions of non-DSN sites. We estimate their positions with an *a priori* standard deviation of 1 km.

In practice, sub-meter GPS orbits can be determined with approximately 8 hours of carrier phase and pseudorange data [*Lichten and Border*, 1987]. In previous studies (Larson et al., "Report to the GFO GPS Receiver Working Group"), GPS epoch states were unconstrained (*a priori* standard deviation of 1 km for initial position) and satellites were tracked over a long enough period to reduce the formal uncertainty to less than 1 meter. Because of the 30 second batch size used in this study and dimensional limitations in the OASIS software, measurements could only be produced for a 2 hour time span. Therefore, we slightly constrained the GPS epoch states, to 10 m for the initial position, and 1 mm/sec for velocity. We did not constrain the SALT epoch state - using an *a priori* standard deviation of 1 km and 10 cm/sec for the initial position and velocity, respectively. In addition, carrier phase ambiguities were estimated for each satellite-receiver pair. Since the Rockwell receiver doesn't have carrier phase data, no carrier phase ambiguities are estimated for observations between SALT and the GPS satellites. Rather than eliminating GPS satellite and receiver clock errors by differencing the observables, we used undifferenced pseudorange/range-rate data for the Rockwell receiver, and carrier phase/pseudorange data for the Topex receiver. We are thus required to explicitly estimate a clock bias at each data epoch for each satellite and receiver [*Lichten and Border*, 1987].

For a complete accounting of SALT orbit errors, we must consider other error sources which have not been modelled. Although we assumed the positions of the DSN sites were perfectly known, the actual uncertainty of their position is on the order of several cm. In order to determine the effect of so-called "fiducial" errors, we have considered an uncertainty of 5 cm for each component of each station position. A lumped partial for uncertainties in the gravity coefficients was also computed and considered as a potential error source. The lumped parameter consisted of 50% of the GEM-T2 uncertainties for harmonic coefficients up to degree and order 20 [*Marsh et al.*, 1990]. In this treatment, correlations between the gravity coefficients are ignored. This is a conservative treatment; the gravity field error contribution should be smaller than we have calculated. Although in practice we would estimate a tropospheric zenith delay for each ground station, in this study we want to determine the effect of an error in that tropospheric zenith delay. The size of the tropospheric zenith delay varies from 200 to 250 cm, depending on the elevation of the site and local atmospheric conditions. For our consider analysis, we assumed an error of 1 cm in the zenith delay, which is consistent with previous studies [*Mitchell*, 1990]. Finally, we considered several smaller order terms. The consider error for GM was determined for 1 part in 10^8, atmospheric drag at 10%, and solar radiation pressure at 10%, using models described by *Wu et al.* [1986].

Results

The radial orbit precision for the Rockwell and Topex receivers are shown in Tables 5 and 6. For each receiver-type, two solutions are shown. In the first case, 10 ground tracking stations were used (Networks A, B, and C). For the second case, only the 6 primary stations (Networks A and B) were used. For each receiver-type, 10 stations provide more precise SALT orbits than 6 stations, even though the positions of the 7 non-fixed stations are estimated with standard deviations of 1 km. In a previous study (Larson et al., "Report to the GFO GPS Receiver

Working Group"), no improvement was found when the tracking network was increased from 10 stations to 14 stations.

The SALT radial formal errors for the Rockwell and Topex receivers are shown in Figure 2. For a 10 station ground network, the Rockwell and Topex RMS formal errors are 24.9 and 1.9 cm, respectively. The 6 station solutions are also shown in Figure 2. With this configuration, the Rockwell radial orbit error is increased to 43.5 cm. The Topex radial formal error is 7.0 cm - but would be reduced to 4.1 cm if the tracking positions were estimated with tighter constraints (standard deviation of 10 cm rather than 1 km). Likewise, the Rockwell radial formal error using a 6 station ground network is improved to 34.2 cm if the tracking positions are estimated with tighter constraints. We also computed solutions where the data weights for the Rockwell and Topex receiver data weights were increased by 50%. For this case (and a 10 station ground network), the Rockwell and Topex radial formal errors increased to RMS values of 34.5 and 2.4 cm, respectively.

The consider errors we computed are also shown in Tables 5 and 6. As expected, the solar pressure and atmospheric drag consider error contribution is small - consistent with the short arc of SALT data. The contribution from fixing 3 fiducial sites is ~ 2 cm, slightly smaller for a 10 station-Topex receiver solution. The gravity error signature is quite different for the two receivers - *although both receivers exhibit large errors at the beginning and end of the data arc.* The RSS value at each time epoch, i, is defined:

$$\text{RSS (i)} = \sqrt{\text{formal}^2 + \text{stn error}^2 + \text{gravity}^2 + \text{GM}^2 + \text{atm drag}^2 + \text{sol press}^2 + \text{tropo}^2}$$

We then define the "total error" as the RMS of the individual RSS values:

$$\text{total error} = \sqrt{\frac{\sum_{i=1}^{N} \text{RSS(i)}^2}{N}}$$

where N is the number of time epochs, which for Tables 5 and 6 is 11. Figure 3 is a histogram of error contributions for the two receivers studied. For the Rockwell receiver, the receiver data noise (formal error) is the largest contributor to the total error, whereas the Topex total error is dominated by gravity. For 10 station networks, the total error is 27.8 and 16.1 cm, for the Rockwell and Topex receivers, respectively. For a 6 station network, the total error is 45.5 and 25.1 cm for the Rockwell and Topex receivers. For the Topex receiver, other studies have shown that a reduced dynamic technique will reduce total errors to the 5-7 cm level [*Lichten*, 1990]. The reduced dynamic approach becomes less effective as the number of spacecraft receiver channels is decreased, and would not greatly improve the Rockwell orbit errors.

Conclusions

When a 21 satellite GPS constellation and 6 station ground network is used, the Rockwell (SPINSAT) receiver has a radial precision of 45.5 cm. While our assessment of the gravity error contribution was conservative, other factors require further study. The effect of selective availability and anti-spoofing need to be taken into account if the Rockwell receiver is to be launched at a future date. Anti-spoof would reduce the range measurement precision to C/A levels - 8 meters rather than 2.5 meters used in this study. Anti-spoof would also limit the dual frequency ionospheric correction. Selective availability would degrade one's ability to smooth measurements to common epochs. A better assessment of ionospheric errors is needed, although the ionospheric error at the SALT altitude is much less than the ionospheric error for ground stations. Clearly, the Rockwell radial orbit accuracy is highly dependent on the pseudorange data weight we assumed. Thus far, we assumed that the precision of this measurement could be averaged down from its 1 second value. Satellite multipath can seriously contaminate the pseudorange measurement, and thus degrade SALT orbit precision. These error sources could contribute to a radial precision approaching 60 cm.

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Table 1
Receiver Specifications

	Pseudorange	Carrier Phase	Range rate	Integration time
Rockwell SPINSAT:	200-250 cm	none	3-7 cm/sec	1 second
Motorola TOPEX GPSDR:	60 cm (max)	< 1 cm	none	1 second

Table 2
Covariance Analysis Ground Tracking Network

Station	Status	Latitude	Longitude	Measurement History
NETWORK A				
1) Goldstone	TOPEX	35	243	DSN (VLBI,GPS)
2) Canberra, Australia	TOPEX	-35	149	DSN (VLBI,GPS)
3) Madrid, Spain	TOPEX	40	356	DSN (VLBI,GPS)
NETWORK B				
4) Japan	TOPEX	39	141	GPS
5) Brazil	TOPEX[1]	-23	314	GPS
6) South Africa	TOPEX	-26	28	GPS
NETWORK C				
7) Kokee	CIGNET	22	200	GPS,VLBI
8) Westford	CIGNET	42	288	GPS,VLBI,SLR
9) Richmond	CIGNET	25	279	GPS,VLBI,SLR
10) Wetzell	CIGNET	49	13	GPS,VLBI,SLR

1. Operational TOPEX site has been located in Santiago, Chile.

Table 3

SALT Receiver Simulation

Tracking simulation:

Case I.		Comment
Receiver:	Rockwell SPINSAT	
satellite selection:	best PDOP	
channels:	2	
frequencies:	primarily L_1, with occasional L_2 measurements.	
data types:	p-code pseudorange, range rate	
batch interval:	30 seconds	see text
data weights:		
ground network[1]:	31 cm pseudorange, 1.55 cm carrier phase	*Wu et al., 1989*
spacecraft:	215 cm pseudorange, 5.4 cm/sec range rate	*Weninger et al.*, 1989
Case II.		
Receiver:	Topex GPSDR	*Galbraith*, 1990
satellite selection:	long carrier phase tracking	
channels:	6	
frequencies:	simultaneous L_1 and L_2 measurements.	
data types:	p-code pseudorange, carrier phase	
batch interval:	300 seconds	
data weights:		
ground network[1]:	10 cm pseudorange, 0.5 cm carrier phase	*Wu et al.*, 1989
spacecraft:	10 cm pseudorange, 0.5 cm carrier phase	*Wu et al.*, 1989

1: Ground network data weights are consistent with batch intervals. In other words, the 30 second data weights are identical to the 300 second data weights assuming a $\sqrt{N}$ improvement ($\sqrt{10}$ = factor of 3.1).

Table 4
Filter Strategy

Estimated parameters	*a priori standard deviation*	*Comments*
SALT initial position	1 km	dynamic solution
SALT initial velocity	10 cm/s	
GPS initial position	10 m	dynamic solution
GPS initial velocity	1 mm/s	
GPS, GFO, station clocks	1 second	white noise
Group B Cartesian coordinates	1 km	GPS history
Group C Cartesian coordinates	1 km	VLBI,SLR,GPS history
Carrier phase ambiguities	1 km	
Considered parameters	*Uncertainty*	*Comments*
Group A Cartesian coordinates	5 cm	Long VLBI history, DSN
Troposphere zenith delay	1 cm	*Wu et al., 1989*
Lumped gravity	50% GEM-T2	*Marsh et al.*, 1990
Earth GM	1 part in 10^8	*Wu et al., 1985*
Atmospheric drag	10%	Jacchia-Walker
Solar pressure	10%	*Wu et al., 1989*
Elevation angle cutoff:		
ground receivers:	10 degrees	
SALT:	0 degrees	

Table 5
Rockwell Receiver - Radial Orbit Error (cm)

10 Ground Stations (Networks A, B, & C)

Time (min)	RSS	Formal Error	Stn Err	Gravity	GM	Atm drag	Sol press	Tropo
0.	39.0	26.0	1.9	28.9	2.3	0.1	2.2	1.6
12.	29.1	27.8	2.2	8.0	2.5	0.1	1.2	3.3
24.	27.0	26.7	2.4	2.2	2.5	0.0	0.2	3.7
36.	23.8	23.6	2.1	0.9	2.4	0.0	0.3	2.3
48.	22.8	21.6	1.9	6.5	2.3	0.0	0.1	1.0
60.	22.5	21.7	2.1	4.9	2.2	0.0	0.4	2.9
72.	22.5	22.3	2.4	0.8	2.1	0.0	0.5	3.7
84.	23.4	23.0	2.3	3.0	2.1	0.0	0.1	2.8
96.	25.5	25.0	2.0	4.3	2.3	0.0	0.3	1.3
108.	28.3	27.3	2.0	6.8	2.4	0.0	0.0	2.7
120.	35.8	27.3	2.3	22.9	2.5	0.0	0.9	3.8
RMS	27.8	24.9	2.2	11.9	2.3	0.0	0.8	2.8

6 Stations (Network A & B)

Time (min)	RSS	Formal Error	Stn Err	Gravity	GM	Atm drag	Sol press	Tropo
0.	52.5	42.8	2.0	30.3	2.6	0.1	2.1	2.5
12.	49.8	49.4	2.2	4.8	2.7	0.1	1.1	3.5
24.	49.4	49.3	2.2	1.2	2.6	0.0	0.1	2.8
36.	39.7	39.5	2.0	2.8	2.5	0.0	0.3	1.0
48.	32.6	31.9	1.9	6.1	2.3	0.0	0.0	1.7
60.	37.7	37.5	2.0	2.5	2.1	0.0	0.5	2.8
72.	43.9	43.7	2.0	2.2	2.1	0.0	0.6	2.4
84.	42.8	42.4	2.0	4.9	2.3	0.0	0.2	0.7
96.	41.5	41.2	1.9	3.9	2.5	0.0	0.3	1.8
108.	48.1	47.0	2.1	9.4	2.7	0.0	0.1	3.3
120.	56.9	50.3	2.2	26.4	2.7	0.0	0.7	3.2
RMS	45.5	43.5	2.0	12.9	2.5	0.0	0.8	2.5

Table 6
Topex Receiver - Radial Orbit Error (cm)

10 Stations (Networks A, B, & C)

Time (min)	RSS	Formal Error	Stn Err	Gravity	GM	Atm drag	Sol pres	Tropo
0.	7.4	2.0	1.0	6.1	3.5	0.1	2.2	1.0
12.	28.3	2.3	0.8	28.0	3.7	0.1	1.2	1.4
24.	12.3	2.0	1.0	11.6	3.4	0.0	0.2	1.1
36.	5.3	1.6	1.3	4.1	2.6	0.0	0.3	0.4
48.	17.7	1.7	1.3	17.5	1.8	0.0	0.0	0.6
60.	15.1	1.9	1.0	14.9	1.4	0.0	0.4	1.0
72.	3.1	1.9	0.9	1.5	1.7	0.0	0.5	0.8
84.	15.5	1.6	1.1	15.2	2.4	0.0	0.1	0.3
96.	26.1	1.9	1.1	25.8	3.2	0.0	0.3	0.8
108.	15.9	2.2	0.9	15.3	3.7	0.0	0.0	1.3
120.	10.2	2.2	0.9	9.2	3.6	0.0	0.9	1.2
RMS	16.1	1.9	1.0	15.7	2.9	0.0	0.8	1.0

6 Stations (Network A &B)

Time (min)	RSS	Formal Error	Stn Err	Gravity	GM	Atm drag	Sol press	Tropo
0.	56.8	7.4	2.0	56.2	2.6	0.1	2.2	1.4
12.	12.0	8.8	2.0	7.5	2.6	0.1	1.1	1.6
24.	8.1	7.2	1.5	2.1	2.6	0.0	0.1	1.1
36.	10.8	4.1	1.4	9.6	2.4	0.0	0.3	0.2
48.	7.2	5.0	1.8	4.2	2.3	0.0	0.1	1.0
60.	9.0	7.3	1.9	4.4	2.2	0.0	0.7	1.4
72.	17.2	7.0	1.4	15.5	2.2	0.0	0.8	1.1
84.	24.6	5.3	1.2	23.9	2.3	0.0	0.3	0.4
96.	26.0	6.4	1.8	25.0	2.5	0.0	0.2	1.1
108.	28.8	8.6	2.1	27.3	2.6	0.0	0.1	1.6
120.	29.3	8.1	1.7	28.0	2.6	0.0	0.8	1.4
RMS	25.1	7.0	1.7	24.0	2.5	0.0	0.9	1.2

Figure 1.

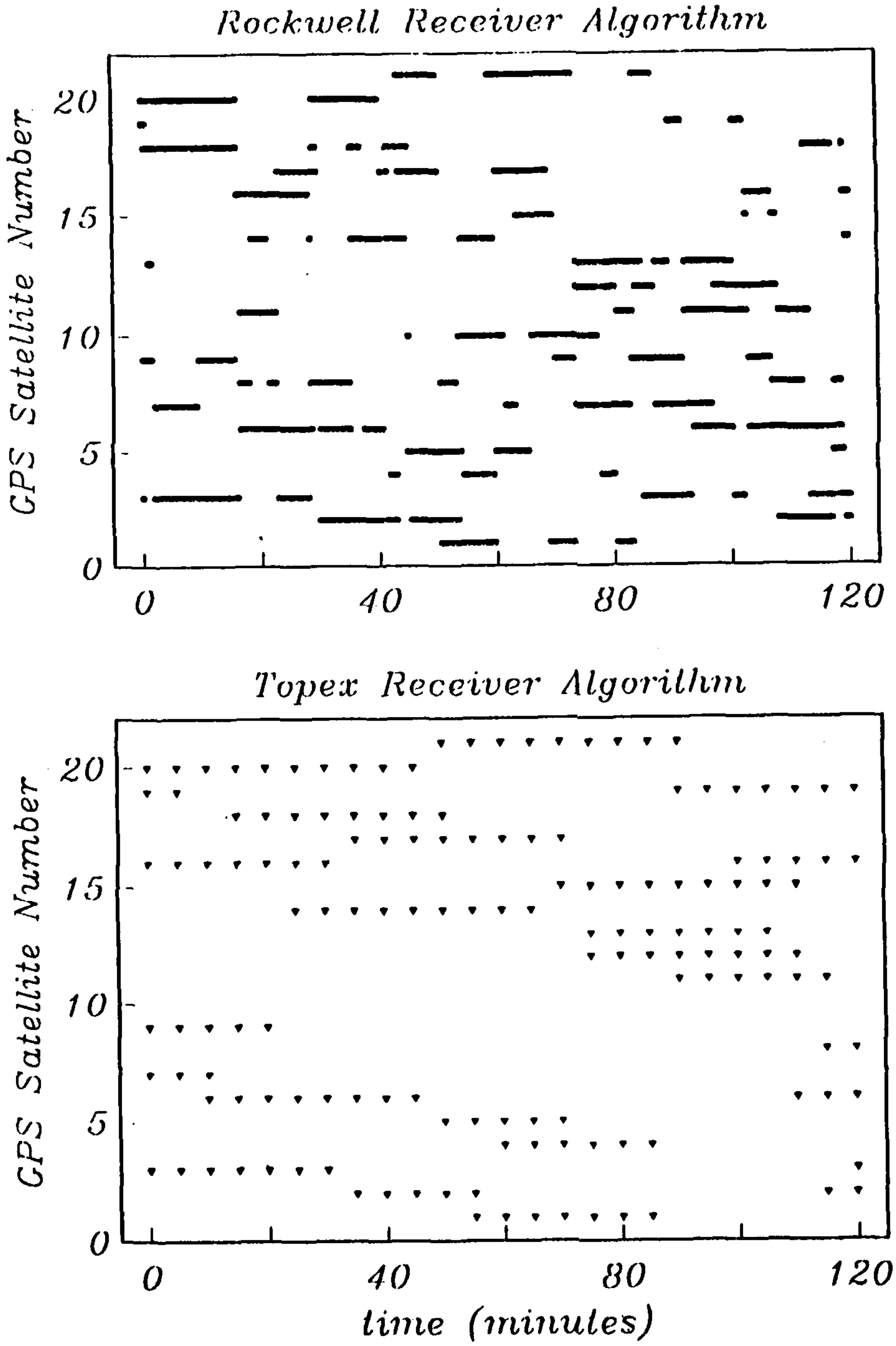
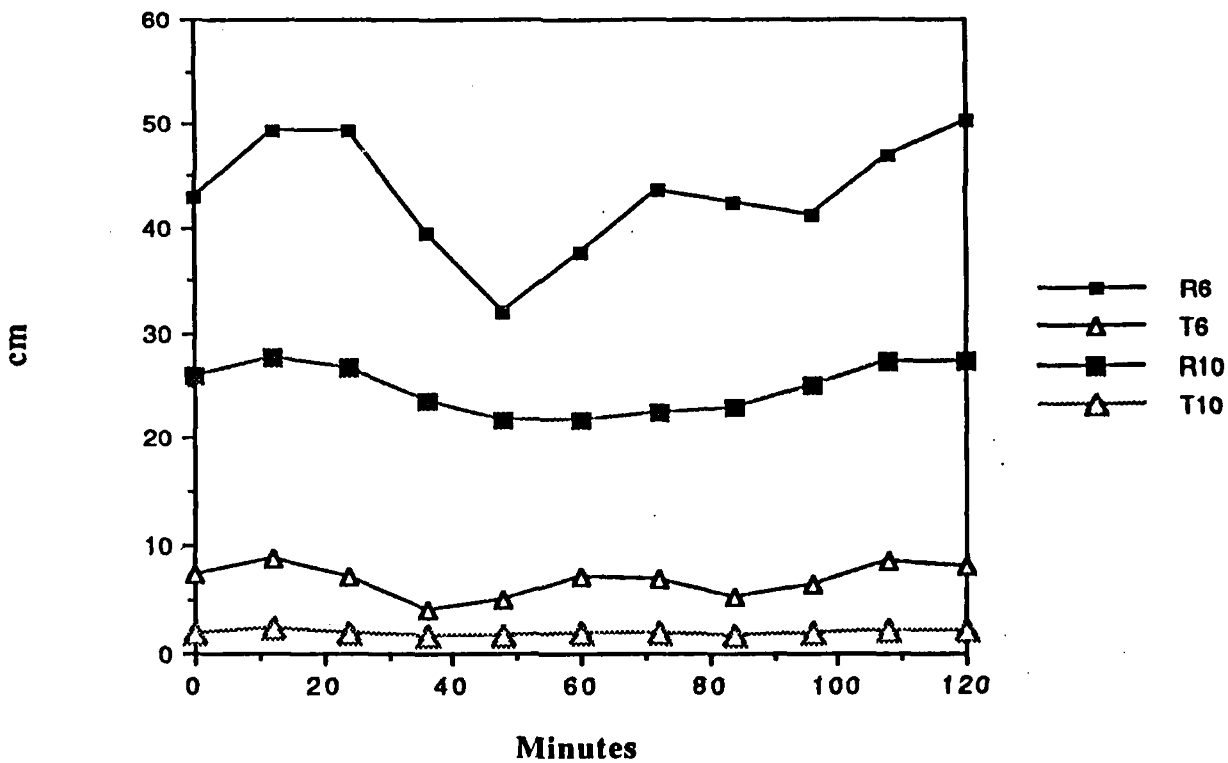

Rockwell Receiver Algorithm
GPS Satellite Number
0
5
10
15
20
0
40
80
120
Topex Receiver Algorithm
GPS Satellite Number
0
5
10
15
20
0
40
80
120
time (minutes)

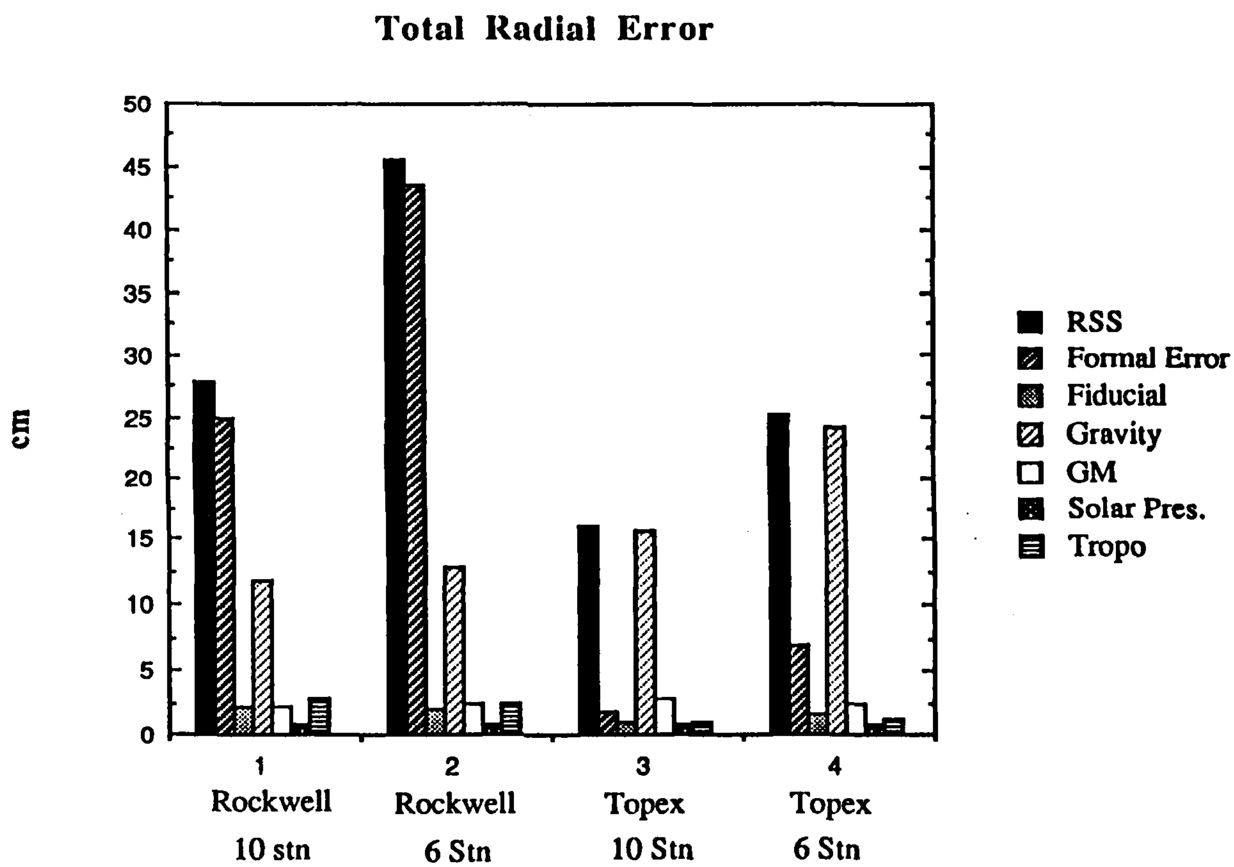
Figure 2

Formal Errors



R6 - Rockwell, 6 station ground network, RMS 43.5 cm
T6 - Topex, 6 station ground network, RMS 25.1 cm
R10 - Rockwell, 10 station ground network, RMS 24.9 cm
T10 - Topex, 10 station ground network, RMS 16.1 cm

Figure 3


Total Radial Error
50
45
40
35
30
25
20
15
10
5
0
cm
1
Rockwell
10 stn
2
Rockwell
6 Stn
3
Topex
10 Stn
4
Topex
6 Stn
RSS
Formal Error
Fiducial
Gravity
GM
Solar Pres.
Tropo